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A Water Vapor Monitor Using Differential Infrared Absorption

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A WATER VAPOR MONITOR USING DIFFERENTIAL INFRARED ABSORPTION

by

Darrell E. Burch and David S. Goodsell
Ford Aerospace & Communications Corporation
Aeronutronic Division
Newport Beach, California 92660

Contract No. 68-02-3238

Project Officer

William McClenny
Atmospheric Chemistry and Physics Division
Environmental Sciences Research Laboratory
Research Triangle Park, North Carolina 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
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Abstract

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SECTION 1

INTRODUCTION

The Environmental Protection Agency has encountered a problem of obtaining the mass of H_2O associated with ambient air particulate matter that has been collected on Teflon filters. This measurement is needed to estimate the contribution of H_2O to the deficit in mass between the total measured aerosol mass and the mass that can be attributed to currently measurable particulate components. This deficit is as much as 30% in some cases.[1] A positive and quantitative identification of H_2O poses an analytical problem for several reasons: (1) the amount of H_2O is small, i.e., 30% of a typical loading of 500 µg of aerosol per filter is only 150 µg; (2) the H_2O associated with the particulate matter is not accessible; (3) volatilization of H_2O from the filter by heating also volatilizes other aerosol components so that a simple measurement of weight loss is not acceptable as an indication of H_2O on the filter. However, volatilization of the H_2O coupled with a sensitive H_2O monitor capable of a real-time output was conceived as a tenable approach provided that the H_2O vapor concentration was sufficiently high (parts-per-thousand range) to achieve a reasonable signal to noise as an output signal. Previous research for the EPA concerned with the design and fabrication of prototype instruments for the detection of CO_2[2] and CH_4[3] at ambient air concentrations has resulted in highly successful procedures for using infrared absorption as the basis for sensitive and specific ambient air monitors. Considerations based on this analogous work indicated that the H_2O could be detected if thermal desorption over a period of 1-2 minutes occurred into a carrier gas volume of 50-100 cc. A previous EPA contract had resulted in a prototype[4] unit capable of effecting the thermal desorption of volatile aerosols into a sulfur detector (for H_2SO_4 detection). This prototype was to be used for the detection of aerosol-associated H_2O by replacing the sulfur detector with a H_2O monitor.

SECTION 2

SUMMARY

A water vapor monitor based on absorption of infrared radiation has been designed and fabricated as a self-contained unit. This unit is intended for use in measuring the amount of H_2O thermally released from collected particulate matter. Such a measurement is expected to answer the question of whether H_2O is a major weight component on the filters. With this measurement, the current mass deficit between measured mass and the mass of currently measurable particulate components can be clarified.

The monitor consists of a radiation source (tungsten iodide lamp), an optical absorption cell, a PbS detector and associated optical and electronic components. The unit is analogous in many ways to the family of so-called gas filter correlation (GFC) monitors that have been previously designed and fabricated at Ford Aerospace and Communications Corp.[2,3,5]

The concentration of H_2O vapor in the sample cell of the monitor is determined by electronically comparing the transmittance of the sample in two narrow infrared spectral intervals. One interval occurs near 2.59 micrometers where H_2O vapor absorbs much more than in the other interval centered near 2.51 micrometers. Samples of gas containing H_2O vapor may be introduced into the 20-cm long sample cell and kept static during the measurement, or they may flow continuously through the cell. Good stability of the zero-setting and the sensitivity is achieved by controlling the temperatures of the sample cell, spectral filters and detector. Water vapor concentrations as high as 5% can be measured with good accuracy. The minimum detectable concentration in air samples at 1 atm total pressure is less than 10 ppm. Discrimination against interference by other gases, particularly those in the normal atmosphere, is excellent due to the spectral position and width of the spectral filters.

Based on the performance of the monitor during calibration, the monitor appears to be an excellent ambient air monitor, giving a real-time output proportional to the ambient H_2O content. Combined with the temperature and pressure sensors that are included in the instrument, the absolute and relative humidities can be obtained. This type of system may offer significant advantages over other currently available H_2O monitors.

SECTION 3

CONCLUSIONS

The results of tests performed with the monitor indicate that the same basic principles of operation can be applied to a variety of H_2O monitors for many different uses. Very good sensitivity can be achieved by using long optical paths in the sample cell; the minimum detectable concentration of less than 10 ppm achievable with the 40-cm optical path of the present monitor is adequate for most applications. Maximum accuracy is obtained by controlling the electric power voltages and the temperatures of the key optical components. However, the design of other monitors can be simplified if the maximum accuracy and sensitivity are not required.

The volume of the sample cell can be reduced to less than the 56 cm^3 of the present cell if it is necessary to analyze small quantities of sample. Reducing the sample volume significantly requires either: decreasing the cell length and thus decreasing the sensitivity; decreasing the diameter, which decreases the signal-to-noise ratio because of the smaller amount of radiant energy in the monitoring beam; or complicating the cell by including a multiple-pass optical system.

Interference by other gas species in ambient air is not a significant problem because of the good discrimination provided by the spectral position and width of the two infrared spectral intervals, one absorbing and one nonabsorbing, that allow a difference in absorption to be measured when H_2O is present.

SECTION 4

RECOMMENDATIONS

It is recommended that variations of the monitor be considered for many applications in which the concentration of H_2O vapor is to be measured. The required complexity of a monitor of this type depends on the sensitivity, stability, accuracy and time response involved. Therefore, it is not practical to design a single H_2O monitor for all applications. Some of the design features that should be considered for a given application are as follows:

1. The two spectral intervals (λ = 2.59 and 2.51 micrometers) passed by the two filters are appropriate for many applications. If a gas species in the samples absorbs strongly within one of these intervals, a different set of intervals should be selected. It may be advisable to select another spectral interval to replace the 2.59 micrometer interval if the absorption is too great. A different interval is recommended if pL is greater than approximately 2 atm cm (p is the H_2O partial pressure and L is the optical path length through the sample cell.)

2. A PbS detector designed for long wavelength sensitivity is inexpensive, durable, convenient, and adequate for most applications. However, a cryogenically cooled PbS, PbSe, or InSb detector could provide higher sensitivity and possibly better stability when the improved performance is required. Good stability of the zero-setting can be achieved with a PbS detector near room temperature only if the detector is temperature controlled.

3. Controlling the temperature of the filters improves the stability of the zero setting and the span calibration. However, this is not required for many monitoring applications.

4. The electronics that process the detector signal should automatically account for small variations in source radiance, detector sensitivity, window transmittance, etc.

5. The optical path in air outside of the sample cell should be kept short, and if very good stability is required, it should be enclosed for convenient purging or drying with dessicant.

6. Gas lines leading to the sample cell should be heated to reduce adsorption or condensation of H_2O on the walls.

7. The same basic design may be used to monitor gases without drawing them into a sample cell. For example, the monitoring beam may traverse an open volume such as an atmospheric path or an exhaust vent.

SECTION 5

OPTICAL LAYOUT AND PRINCIPLES OF OPERATION

LAYOUT

Many of the design features of the monitor resulted from the following four requirements that were necessary to meet the sensitivity specifications in the Scope of Work of the current contract: (1) an optical path of approximately 40 cm in the sample cell, (2) the optical path in air external to the cell should not exceed a few millimeters and must be enclosed for convenient flushing with dry air or N_2, (3) the sample cell must be temperature controlled and should have a small volume, and (4) the spectral filters and the detector must be temperature controlled. Figures 1 and 2 illustrate the optical layout that was designed to meet these requirements.

All of the optical components of the source optics shown in Figure 1 are contained in a temperature-controlled enclosure (shown in Figure 2) that is flushed with dry N_2 when very accurate measurements are desired. The thick CaF_2 lenses form an image of the tungsten-iodide bulb near the filter wheel with only a few millimeters of optical air path. The sapphire window near the source protects the CaF_2 lens from thermal shock that could cause cleavage.

After passing through the filter wheel, the beam enters the sample cell through a sapphire rod with one convex end; the rod serves as both a window and a field lens. A spherical mirror on the opposite end of the 20-cm long, 1.9 cm I.D. sample cell forms an image of the source near the first surface of the sapphire window that serves as the exit window. This rod is convex on both ends and images the mirror on the PbS detector. Both sapphire windows are sealed to the flange of the sample cell; the entrance window projects into the enclosure to reduce the optical path through air.

The enclosures that contain the filter wheel is controlled at 45?C to maintain constant filter temperature. The PbS detector is mounted on the wall of this enclosure near the temperature sensor so that the detector temperature will remain constant. Variations in the temperatures of the filters and the detector would cause drift in the zero-setting. Insulation not shown in the figures covers the enclosure and the sample cell.

The enclosure, the motor and the sample cell are assembled as a single unit that is mounted with spring loading against 3 hardened-metal spheres. One sphere fits into a cone, one fits into a V-groove, and one rests against a flat surface. This mounting makes the optical alignment insensitive to temperature changes and to distortions of the baseplate.

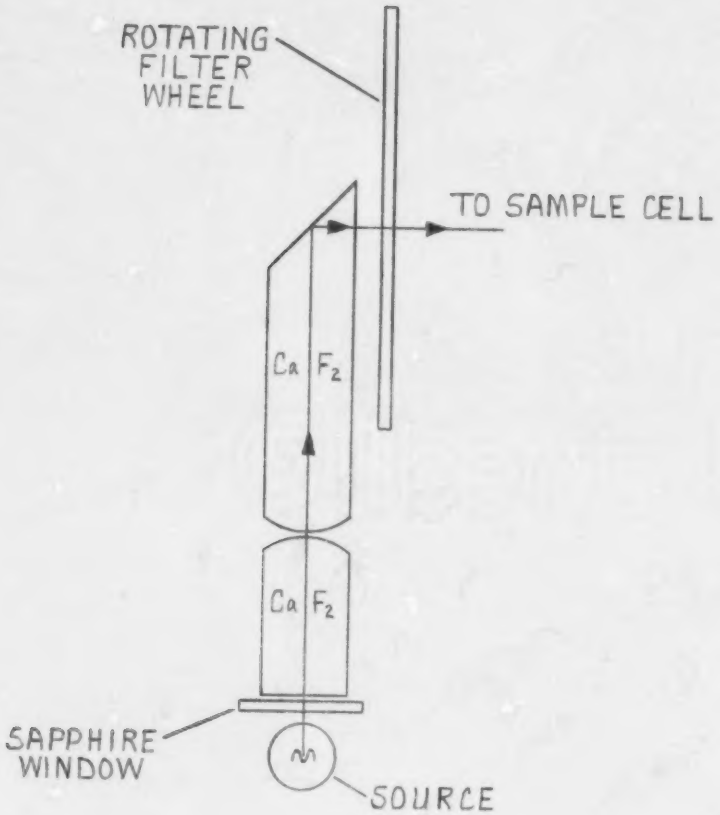

Figure 1. Optical diagram of the source optics. After passing through the filter wheel, the beam enters the sample cell as shown in Figure 2. All of the optical components shown are contained in a temperature-controlled enclosure that is flushed with dry air.

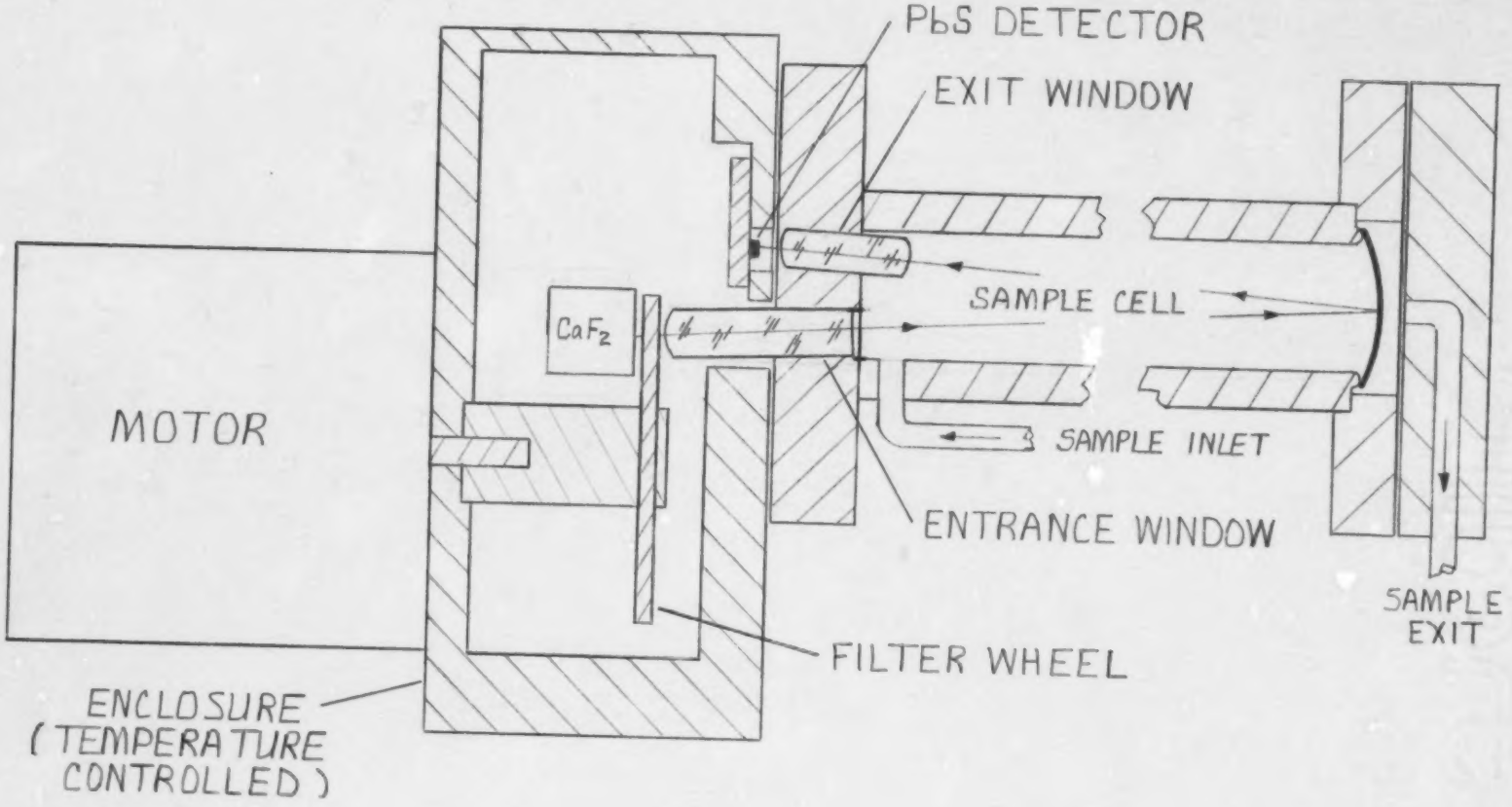

Figure 2. Optical diagram of the sample cell and detector optics. The view is from the side of the monitor. The infrared beam passes through the CaF_2 lenses to the filter wheel as shown in the top view of Figure 1.

SPECTROSCOPIC PRINCIPLES

Filter A, one of the semi-circular spectral filters shown in Figure 3, passes a narrow spectral interval centered near 2.59 micrometers where H_2O vapor absorbs strongly. Filter B passes a narrow spectral interval centered near 2.51 micrometers where the H_2O absorption is much weaker than in the other interval. A 12-spoke reticle deposited on the rotating filter wheel produces a 360-Hz modulation of the monitoring beam. When the sample cell contains no absorbing gas, the 360-Hz component of the detector signal is the same when filter A is in the beam as when filter B is in the beam. When H_2O is added to the sample cell, the absorption decreases the detector signal more when filter A is in the beam than when filter B is in the beam. This produces a 30-Hz modulation of the 360-Hz carrier signal; the fractional demodulation is proportional to the H_2O concentration.

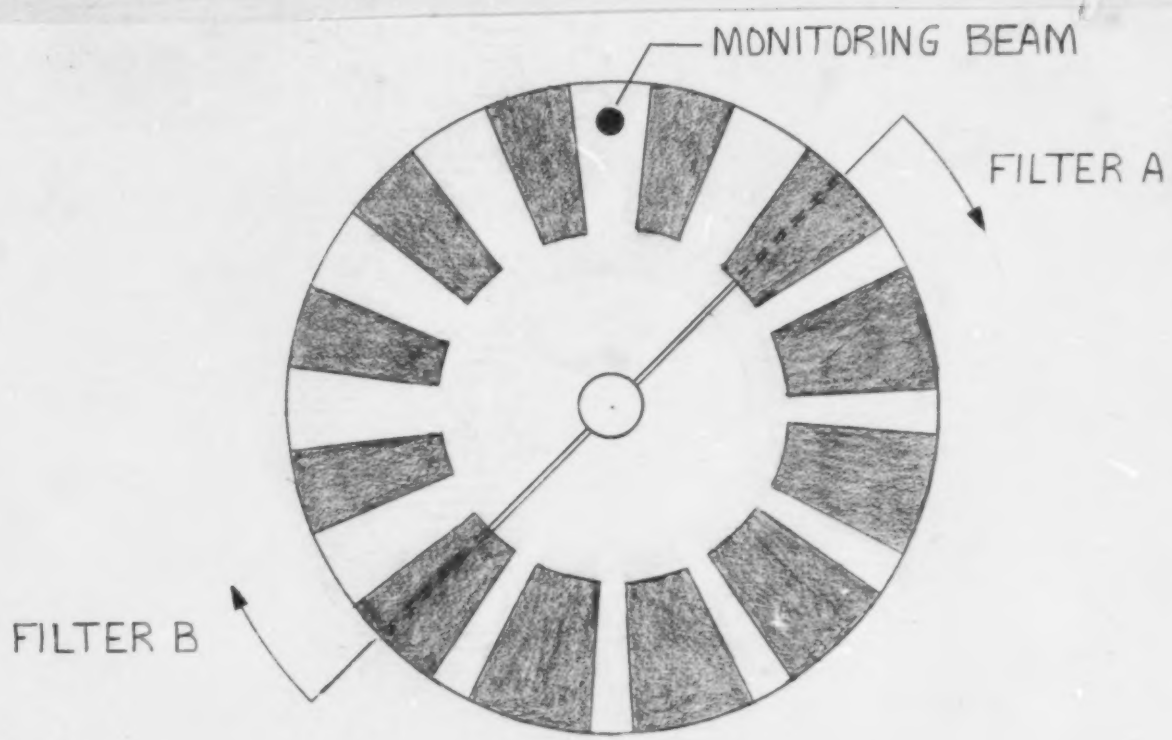

Figure 3. Optical diagram of the filter wheel. The wheel rotates at 30 revolutions per second. Filter A passes a narrow spectral band where the H_2O absorption is much stronger than in the band passed by Filter B.

ELECTRONICS AND PROCESSING OF DETECTOR SIGNAL

The electronics process the signal from the detector and produce a dc voltage that is proportional to the concentration of H_2O in the sample gas. The relationship between the output voltage and the H_2O concentration is determined by calibrating the instrument with samples of known H_2O concentration. A block diagram of the electronics used to process the detector signal is shown in Figure 4. The 360-Hz component of the signal from the detector serves as the carrier for the 30-Hz component that is to be measured. The 30-Hz component of the detector signal resulting from any 30-Hz variation of radiant energy on the detector that is not also chopped at the carrier frequency is rejected by the electronics. The electronics consist basically of two demodulators in series. The first demodulator operates at the carrier frequency, 360 Hz; the average output of this demodulator is proportional to the amount of radiant energy chopped at 360 Hz. If the chopped energy incident on the detector is also modulated at 30 Hz, the 30-Hz component of the output signal from the 360-Hz demodulator is proportional to the modulation. This 30-Hz component then passes through a series of gain controls and amplifiers to the 30-Hz synchronous demodulator. The output of the 30-Hz synchronous demodulator is proportional to the 30-Hz modulation of the 360-Hz signal, and thus to the concentration of H_2O in the sample gas. The reference signal for the 30-Hz synchronous demodulator is supplied by the 30-Hz reference pick-up mounted in the heated enclosure.

During the normal mode of operation, it is desirable that the output signal be proportional to the ratio, $V_a/V_c = V'$, where V_a is the average demodulated 30-Hz component of the detector signal and V_c is the 360-Hz component of the detector signal. The instrument calibration relates the H_2O concentration of the sample gas to V', and it is desired that this relationship be independent of source brightness, detector sensitivity, etc. During the normal mode of operation, V_c is maintained at a constant value by the automatic gain control (AGC) circuits. If, for example, the signal from the detector decreases because of dirt on a window or a decrease in source brightness, the AGC increases the amplification of both the 360-Hz signal and the 30-Hz signal by the same factor. Therefore, V' is kept directly proportional to the output V_a and maintains a constant relationship with the H_2O concentration.

A time constant switch mounted on the main electronics card makes it possible to select an electronic time constant of 0.3, 1, 3 or 10 sec. The main output signal representing H_2O concentration can be determined from the jack labeled "FCN" or from either of two output jacks. A signal that corresponds to a full-scale reading of the panel meter produces a 10-volt dc signal on one of the output jacks. The corresponding full scale reading for the other output jack can be adjusted from less than 1 mv to 10 v. Thus, the instrument can be used with a wide range of recorders or meters, provided the input impedance of the recorder is sufficiently high.

A four-position switch mounted on the main electronics card makes it possible to use the FCN jack to monitor quantities other than the signal output. The 30-Hz reference signal and the average carrier voltage, V_c, can be checked by connecting a microammeter to this jack to see if the signals

are in the correct operating range. When the selector switch is in the "signal-in" position, the signal on the FCN jack is equal to the signal going into the 360-Hz synchronous demodulator. With the selector switch in the "signal out" position, the signal on the FCN jack is equal to the output signal. The signals on the output jacks are not affected by the position of the selector switch.

The 30-Hz reference pickup consists of a light-emitting diode (LED) and a small phototransistor. The 30-Hz pickup is mounted on the heated enclosure. One-half of the rim of the filter wheel is reflective, and the other half is black. As the filter wheel spins at 1800 rpm, the reflected light is sensed by the detector and produces a 30-Hz signal. The amplifier for the 30-Hz reference pickup is tuned and contains an adjustable phase shifter to produce a "clean" signal with the proper phase for the 30-Hz synchronous demodulator.

The zero-balance assembly electronically accounts for any misbalance between the two halves of the gas-filter cell assembly cycle when there is no H_2O in the sample cell. This electronics assembly would not be required if it were practical to maintain a perfect optical balance between the two filters on the filter wheel. Approximately $\pm$ 10 percent variation in the transmittance through either of the two halves of the cycle can be accounted for by this electronic zero-balance assembly. The assembly decreases the amplification ahead of the 360-Hz demodulator during one of the halves of the filter wheel cycle. The proper half of the cycle during which the amplification is changed is selected by a switch on the front panel. A signal from the 30-Hz reference pickup switches the zero-balance assembly between the two different gains with the proper phase. The difference in the gains between the two halves is adjusted with the "zero" potentiometer mounted on the front panel of the instrument.

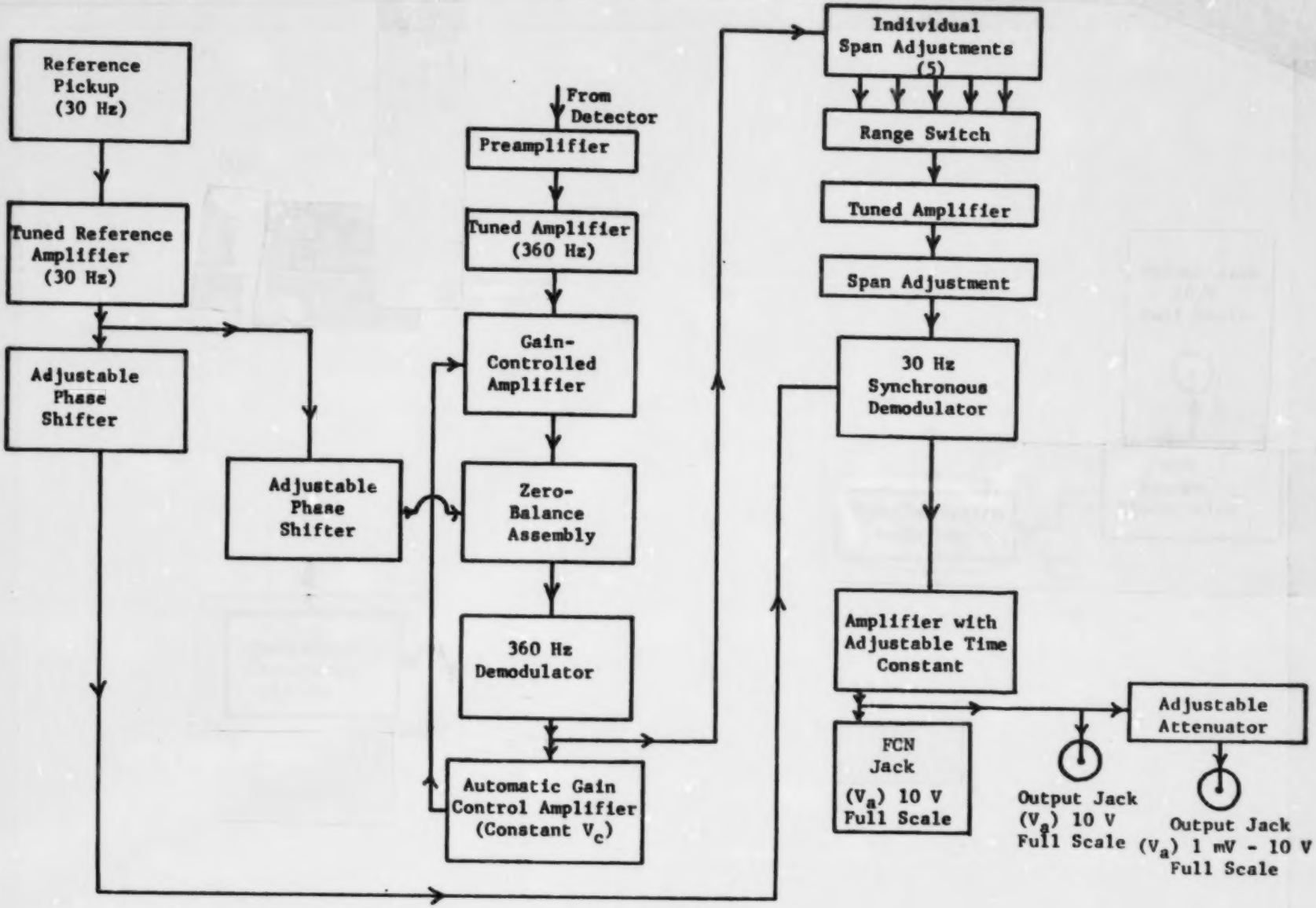

Figure 4. Block diagram of the signal-processing electronics.

SECTION 6

CALIBRATION AND PERFORMANCE TESTS

SPAN CALIBRATION

Data for the span calibration relating output signal to the H_2O concentration were obtained by flushing the sample cell with various known concentrations of H_2O vapor in N_2. The richest mixture, approximately 2.2% H_2O, was formed by slowly bubbling N_2 through liquid water at about 20°C. The bubbling was sufficiently slow that the water evaporated in the N_2 bubbles to the point that the gas leaving the bubbler was saturated. Several dilute mixtures of various concentrations were formed by "blending" the N_2 that had bubbled through the water with dry N_2 from another gas line. The concentration of the resulting mixture was calculated from the measured flow rates in the two lines. As the known mixture was flowing continuously through the sample cell, the output signal on the 10-volt full-scale jack was recorded on a strip-chart recorder. Output signals corresponding to no sample were recorded periodically for comparison by flushing the sample cell with dry N_2. During these tests, the sample cell was controlled at 45°C, the normal operating temperature, and the inlet line was at room temperature.

The span calibration data obtained in this manner with the monitor on the 5% full-scale range were plotted on a log-log scale as voltage versus H_2O concentration. A smooth curve drawn through the points was extrapolated to 5% and to lower concentrations. At concentrations below approximately 0.2%, the output signal is almost directly proportional to the concentration, yielding a straight line of unity slope on a log-log plot. The appropriate potentiometers were adjusted to change the sensitivity so that the plotted curve would pass through the point corresponding to 10 volts at 5% H_2O. The richest mixture, 2.2% H_2O, produces an output signal of 6.6 volts. The sensitivities of the other ranges were then adjusted to force the curves to pass through the point representing 10 volts for H_2O concentrations of 2%, 1%, 0.5% and 0.2%. The resulting calibration curves are shown in Figure 5.

Before making measurements that require good accuracy, the user should check the span calibration with reliable standard samples at H_2O concentrations approximately the same as those to be measured. This is particularly true if the H_2O concentrations are between 2.5 and 5%.

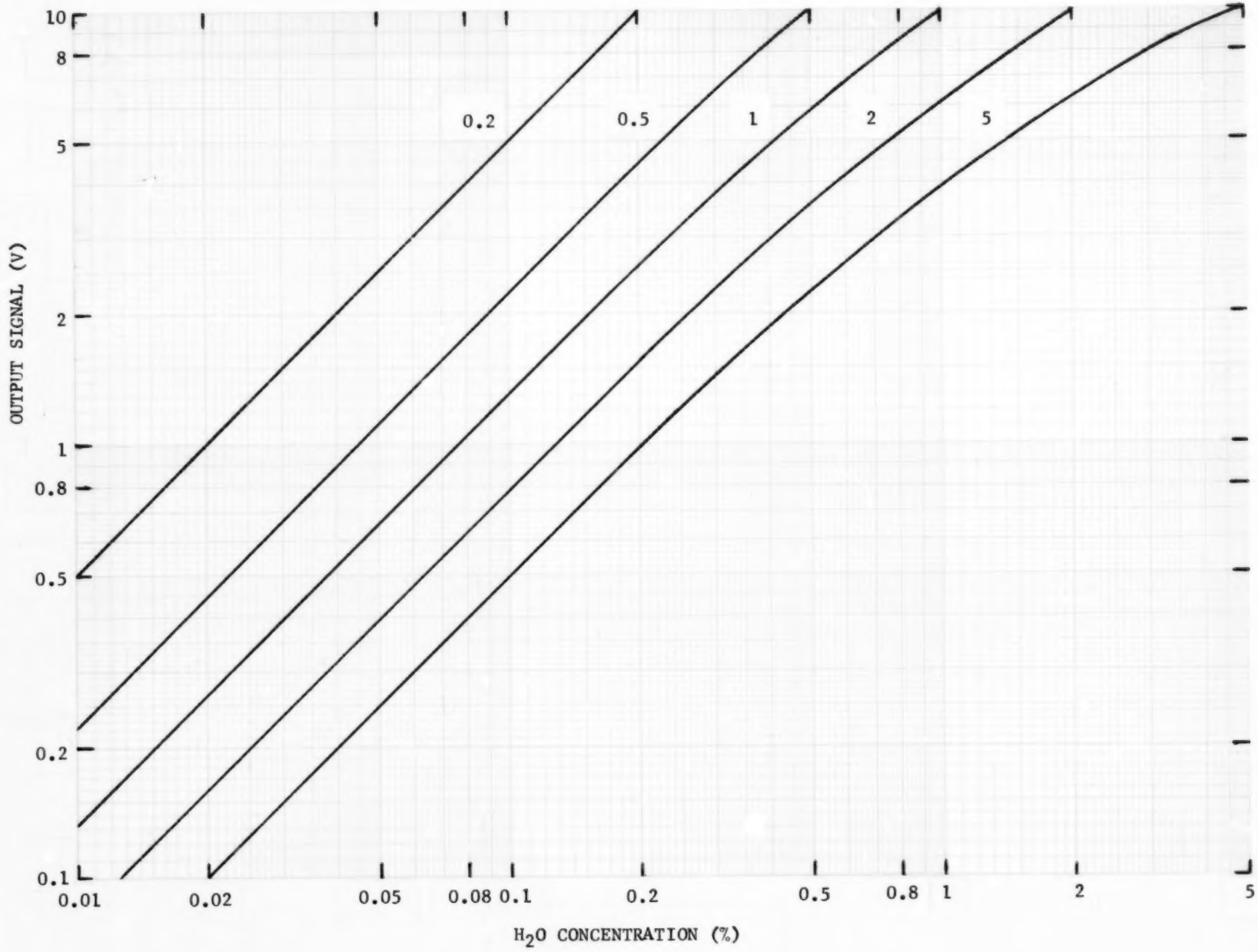

Figure 5. Calibration curve relating the output signal to the H_2O concentration.

INTERFERENCE

The spectral region for detection of H_2O was chosen with reference to previous research[6,7] and with the general knowledge that the fundamental absorption bands of normally occurring ambient gases, other than H_2O and CO_2, do not occur in the selected spectral region (see standard compilations of infrared spectra such as the Statler Index). We selected the spectral filters to avoid the strongest CO_2 absorption bands that are known to occur near 2.7 micrometers. However, some very weak CO_2 lines occur in the region passed by filter A.

To check the interference by CO_2, we filled the sample cell with pure CO_2 gas from a commercial cylinder. This 100% mixture produced an output signal that corresponded to 0.022% (220 ppm) of H_2O. Some of this very small signal may have been due to H_2O impurity from the gas line. Normal air with 330 ppm of CO_2 would therefore produce the negligible interference signal corresponding to less than about 0.07 ppm of H_2O, which is much less than the minimum detectable concentration.

Thus, we can conclude that interference is not a significant problem in ambient air due to the combination of weak or negligible absorption by ambient gases in the selected spectral region and the comparatively lower concentrations of other ambient trace gases as compared to H_2O. Before sampling other gases containing gas species not normally found in air, the user should check for possible interfering gases. The strong absorption bands of hydrocarbons occur at wavelengths greater than 3 micrometers; therefore, these gases are not likely to interfere significantly.

NOISE

Figure 6 shows 3 strips of recorder tracings made with the sample cell being flushed slowly with dry N_2. The 3 strips, recorded at separate times, correspond to 3 different electronic time constants: 1, 3 and 10 seconds. The monitor was set on the 0.2% full-scale range, and the recorder was adjusted to 2 volts full-scale. We note that the root-mean-squared noise represents approximately 2 ppm of H_2O when the electronic time constant is 3 seconds. The noise is even less when measured with a 10-second time constant.

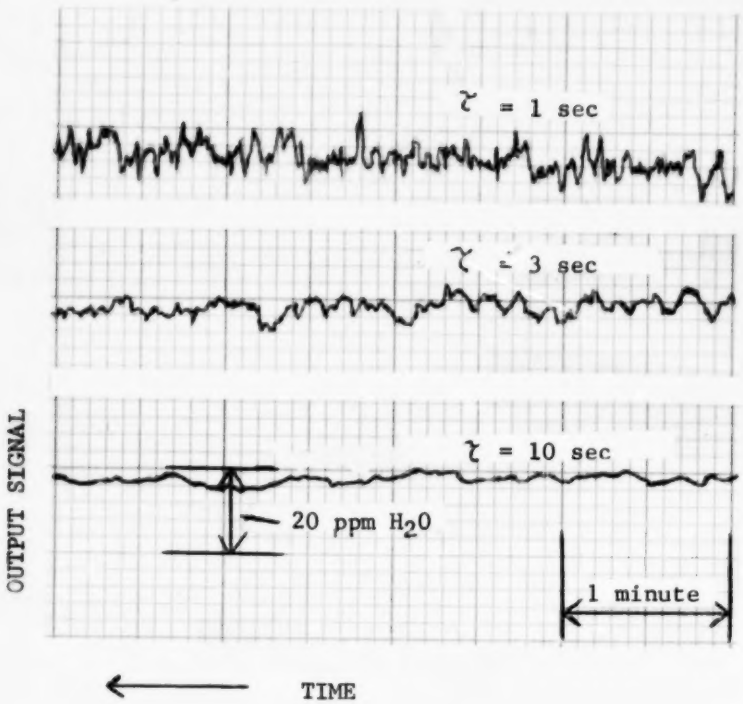

Figure 6. Recorder tracings of the noise on the output signal. Each curve corresponds to the electronic time constant indicated.

ZERO DRIFT

When the monitor is first turned on, the zero-setting (output signal with no H_2O in the sample cell) drifts considerably until the temperatures of the various key components reach equilibrium. Much of the drift observed the first several minutes may be due to changes in the H_2O concentration in the sample cell and in the short path of the optical beam through air outside the sample cell. Water vapor may have accumulated in the enclosure, or some may have adsorbed (or desorbed) on the walls of the sample cell while the monitor was turned off.

Tests of the stability of the zero-setting were performed at 2 different times after the monitor had been turned on for more than 2 hours with the enclosure and sample cell flushed continuously with N_2. In the first test, the variation from the maximum output signal to the minimum for a 1-hour period corresponded to less than 8 ppm of H_2O. The corresponding quantity for the second test performed a few days later was less than 4 ppm. Thus, it is apparent that the care given the optical design and the controlling of the temperatures of key components has led to excellent stability.

SECTION 7

SETUP, OPERATION AND MAINTENANCE

The monitor is 26.7 cm (10.5") high and can be mounted in a standard 19" equipment rack. Three gas connectors are mounted on the back side. One is for the sample inlet, one for sample exit, and one should be connected to N_2 or dry air to purge the enclosure. This purging is not required if the samples have relatively high H_2O concentrations and dry air can be purged through the sample cell frequently to determine the zero setting. The sample cell may be operated at any desired pressure between vacuum and 1 atm above the ambient pressure.

The pressure is measured by connecting a high impedance voltmeter to the output jack labeled "PRESSURE". This jack is connected to a pressure transducer as indicated in the circuit diagrams in Section 7. The signal from the transducer is approximately 37.0 mV per atmosphere absolute. This sensitivity and the zero-reading should be checked if accurate pressure measurements are required. The sample inlet line should be made of stainless steel or some other material on which H_2O does not adsorb readily. Teflon and nylon tubing should be avoided, and the line should be heated to between 40°C and 50°C to reduce the adsorption or condensation of H_2O.

Standard 115-VAC electrical power is the only power required. Care should be taken to ensure that the electrical outlets are wired in the standard manner with the neutral wire in the proper location. Fuses are mounted conveniently on the front panel. The interior of the monitor is cooled by a fan that is built as an integral part of the instrument. However, this method of cooling may not be sufficient if the monitor is mounted in a closed rack with the interior air temperature above approximately 30°C.

The power switch has 3 positions: Off, On and Standby. When the switch is in the Off position, all electrical power is disconnected; when in the Standby position, the heaters remain on to maintain the optical components near the operating temperature. Power is delivered to all of the circuits when the switch is in the On position. Only a few minutes of warm-up is required if the switch has been left in the Standby position. Approximately one hour of warm-up is required for good stability after the instrument has been turned off for several hours. Proper purging of the enclosure may also require several minutes if the enclosure contains moist air

The output signal that is proportional to the H_2O concentration is available on two jacks mounted on the front panel. One jack has a 10-volt signal for full-scale; the full-scale voltage on the other jack may be varied from less than 1 mv to 10 v by use of a switch and a potentiometer mounted on the main electronics card (see Figure 11).

It is advisable to check occasionally the 3 signal levels available on the jack labeled "FCN" by properly positioning the function switch on the main electronics card, which is attached to the inside of the door on the front panel. (See the subsection on electronics in Section 4 and the circuit diagrams in Section 7). These signal levels can be helpful in diagnosing problems and in checking to see if the monitor is operating normally. At the time the monitor was delivered to EPA, the signal levels in microamps were as follows: signal-in, 37 with the monitor warmed up and the sample cell free of any absorbing gas; carrier, 51; and reference, 47.5. If the instrument is operating properly, the carrier level will remain constant because it is determined by the automatic gain control circuits. The reference level may vary by $\pm$ 30% without affecting the performance. The electronics will operate with the signal-in level any place between 20 and 91; however, the stability is best if this level is between 34 and 40 when there is no absorbing gas in the sample cell and the monitor is warmed up. The signal-in level should be adjusted within this range by using the signal-in potentiometer on the main electronics card.

Very little maintenance should be required. The tungsten-iodide bulb has an expected life time of several thousand hours because it is operated at much less than the rated voltage. This bulb can be replaced by removing the back cover and then the bulb holder from the enclosure. In case the interior of the sample cell becomes contaminated, the mirror can be removed by removing the end cap that holds it in place. After the mirror has been cleaned, or resurfaced, it can be put back in place without any alignment being required.

SECTION 8

ELECTRICAL AND ELECTRONIC CIRCUITS

The electrical and electronic circuits are shown in Figures 7-14. The circuits that distribute the 115-VAC power are shown schematically in Figure 7. The main power switch has 3 positions: On, Off and Standby. When the switch is in the Standby position, the heaters and the radiant energy source remain on to maintain the optical components near their operating temperatures.

The electronic components are mounted on 4 printed circuit cards that are connected together as illustrated in Figure 8. Diagrams for each of these cards are shown in Figures 9-12. The main electronics card shown in Figure 11 was designed previously for more complex instruments to monitor either CO or CH_4. The circuits on this card that were originally included for water correction and quadrature correction are not employed in the present instrument. Potentiometers that control the gains of these circuits have been adjusted for zero gain.

Minor changes in the span calibration are made by adjusting potentiometers on the range card shown in Figure 12. Two separate controllers shown in Figure 13 regulate the temperatures of the sample cell and the enclosure. The pressure transducer illustrated in Figure 14 makes it convenient to measure the pressure of the gas in the sample cell.

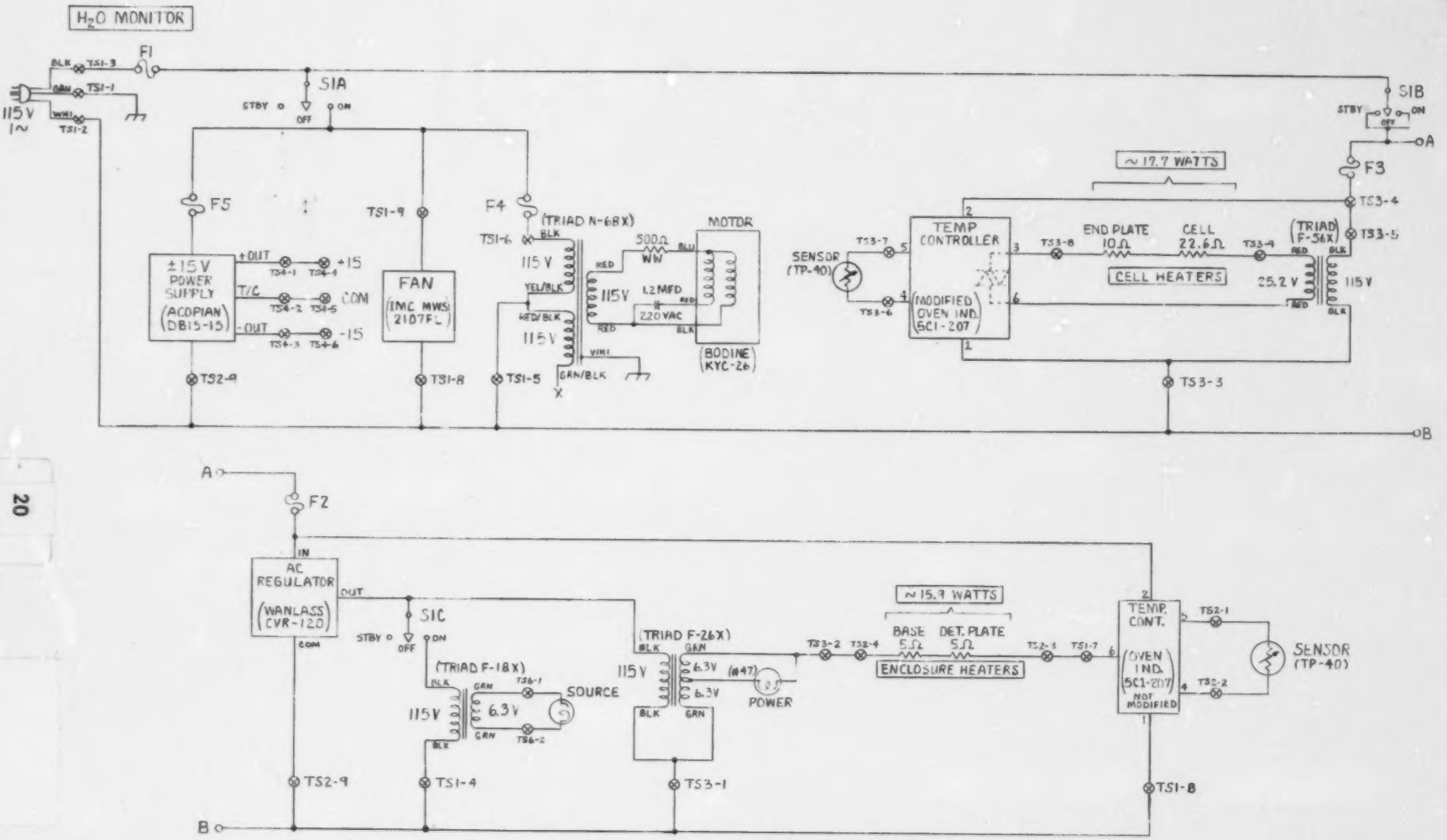

Figure 7. Distribution circuits for the 115-VAC power. The diagram is divided into 2 parts for ease of illustration; points A and B in the upper portion join with the corresponding points in the lower portion.

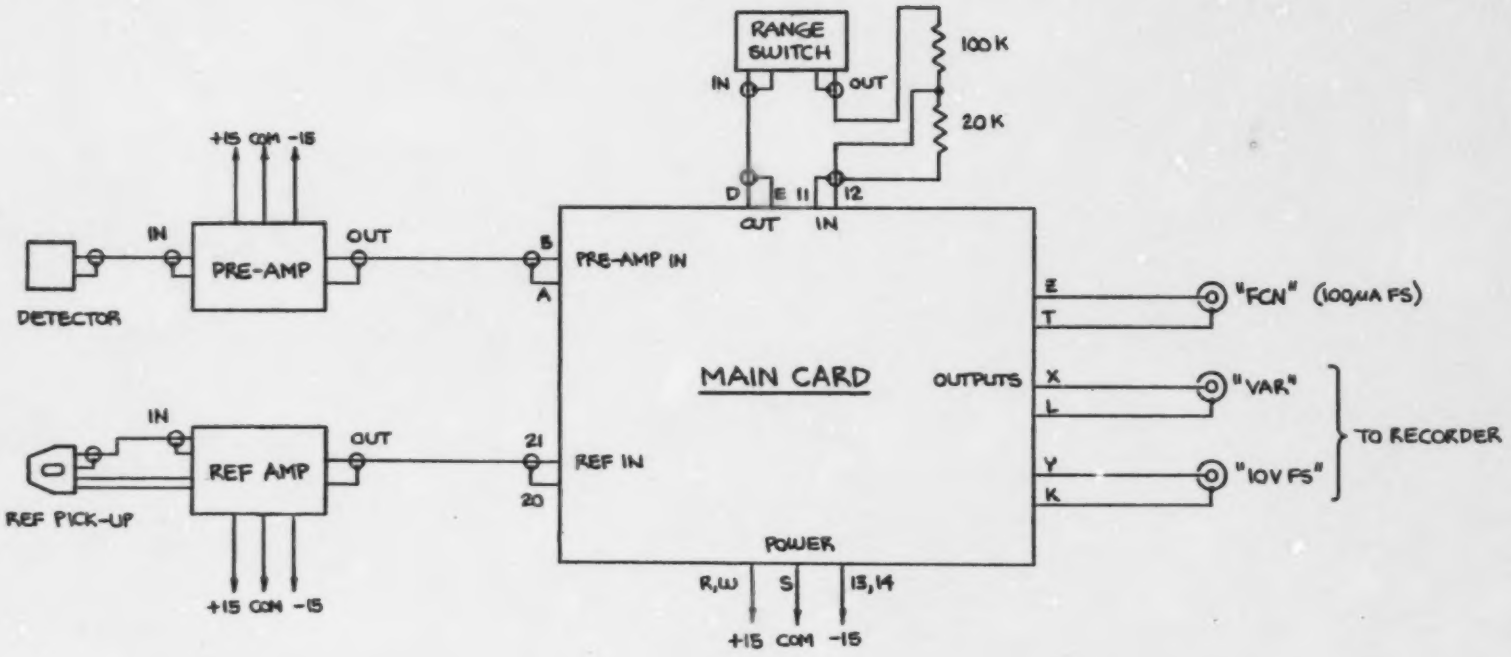

Figure 8. Diagram of the electrical connections among the electronic cards. The jacks labeled "FCN", "VAR" and "10 VFS" are located on the front panel.

NOTES: UNLESS OTHERWISE SPECIFIED

1. ALL RESISTORS ±5% 1/4 W
2. ALL 1% RESISTORS RNC55J TYPE

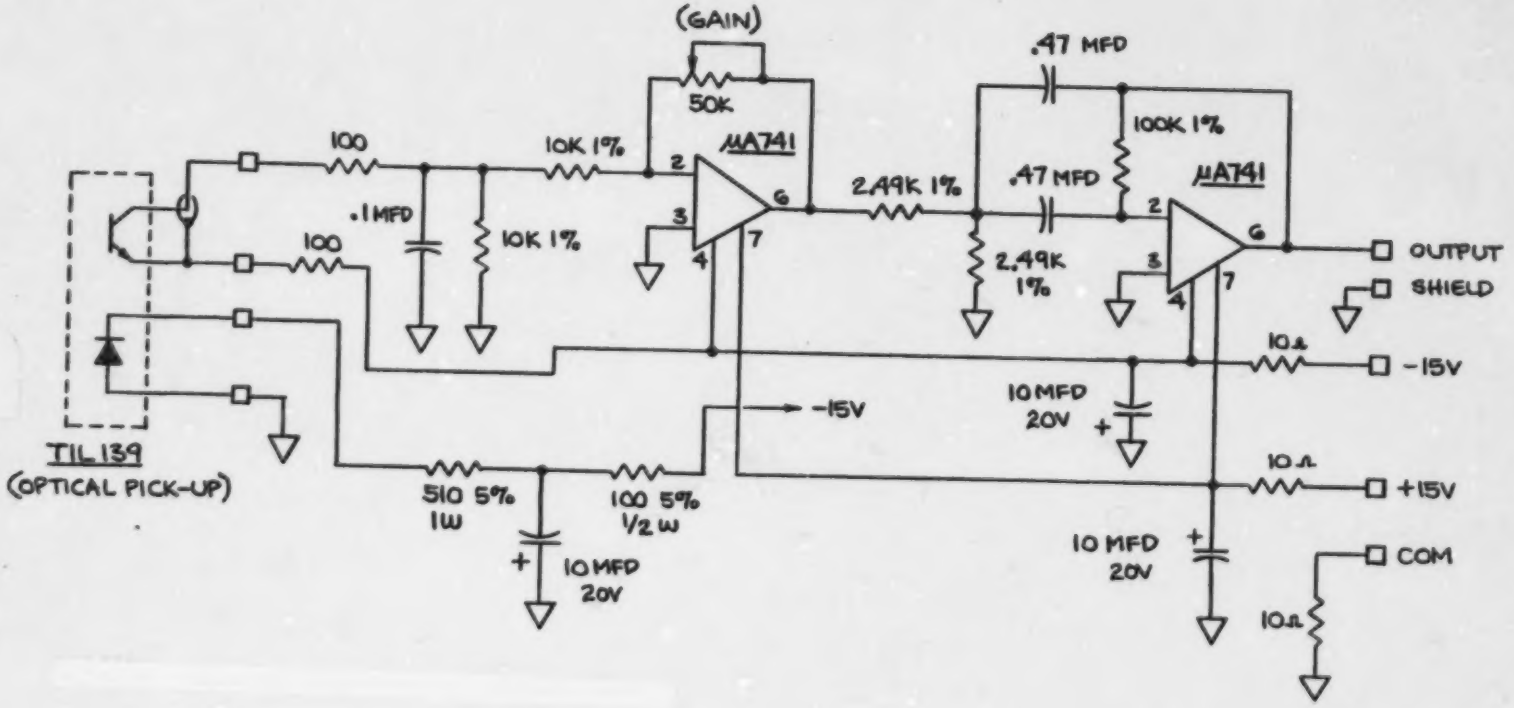

Figure 9. Electronic diagram of the reference card.

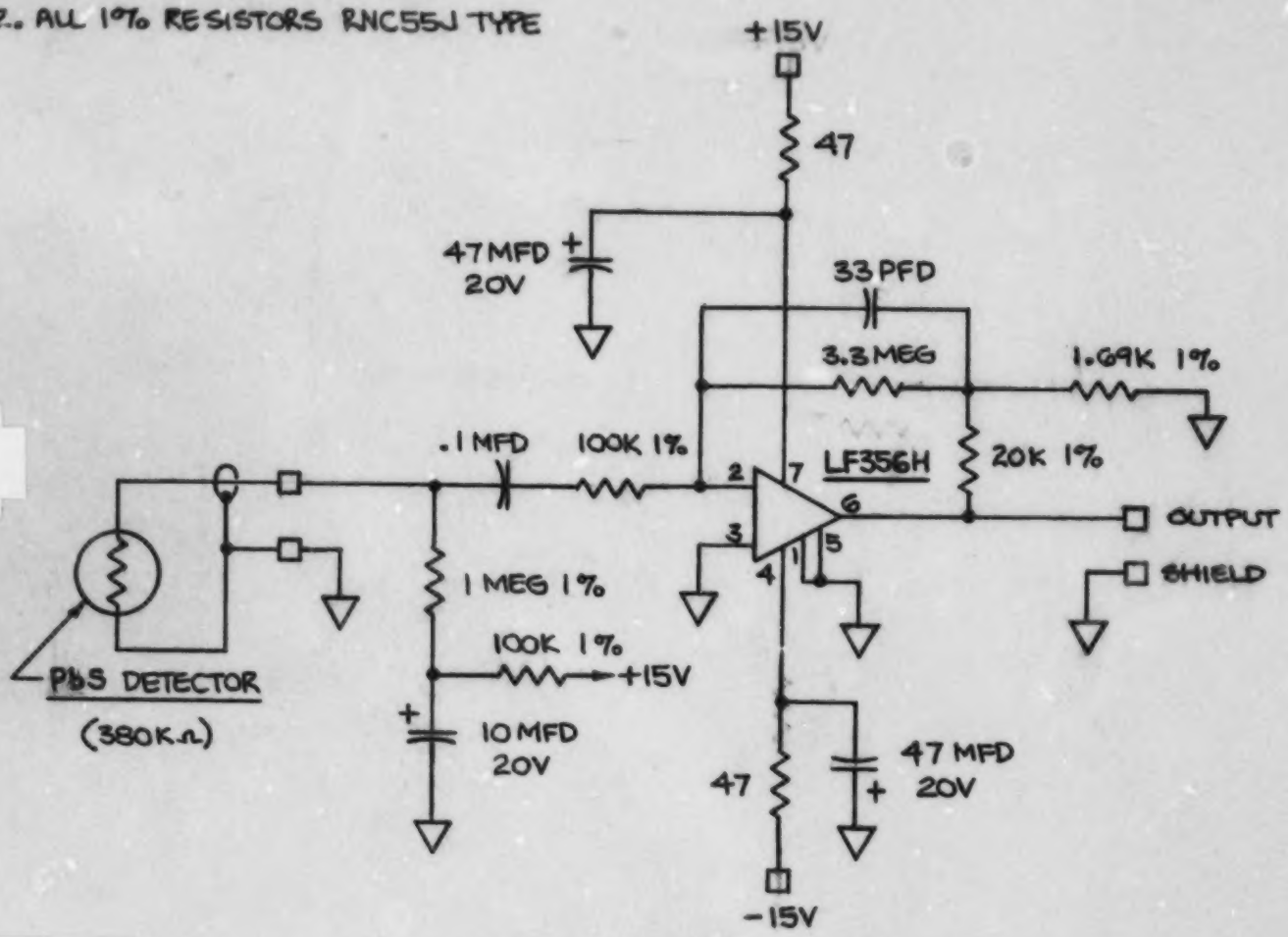

Figure 10. Electronic diagram of the PbS detector and preamplifier.

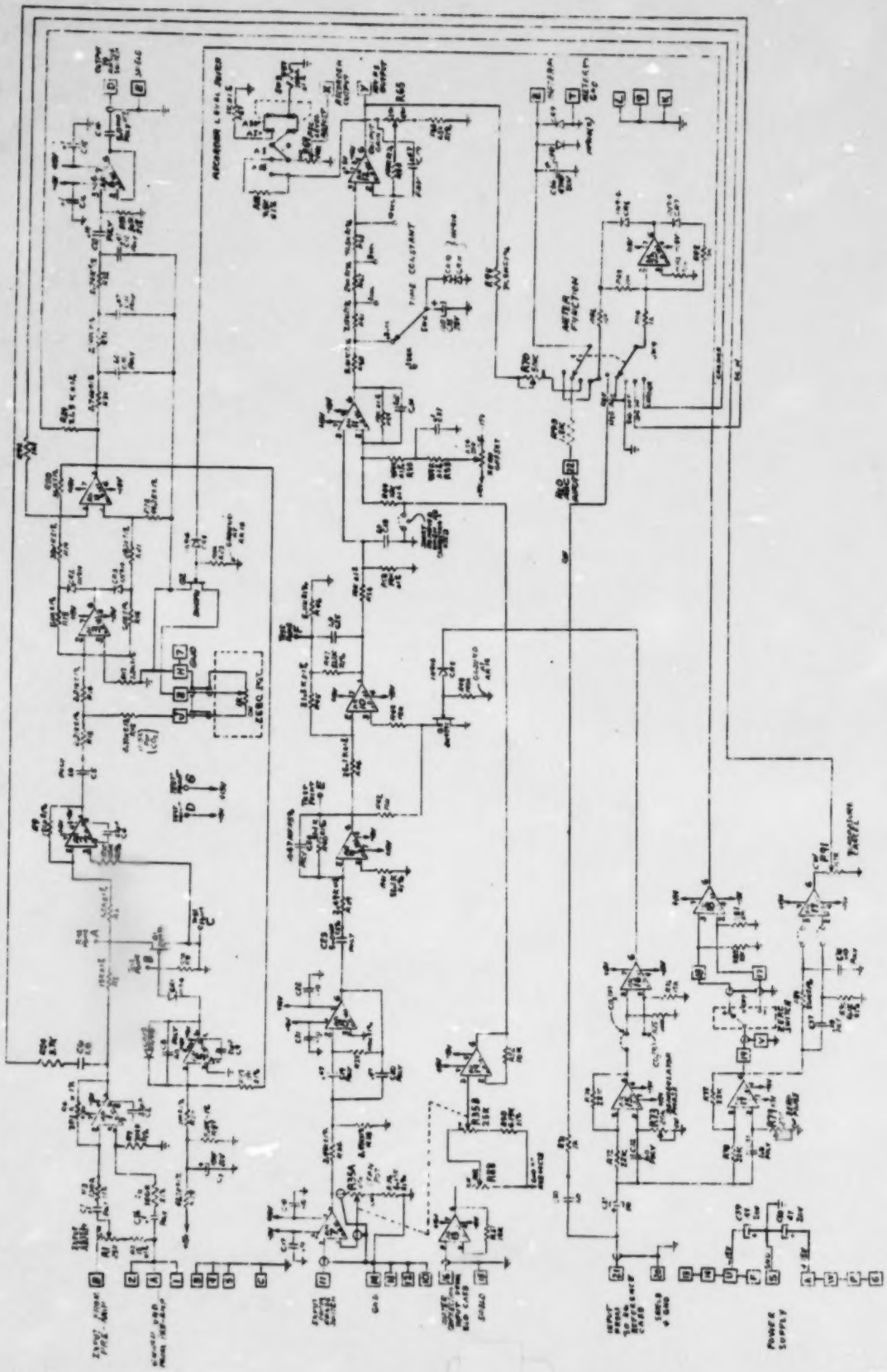

Figure 11. Electronic diagram of the main electronics card.

NOTES:

1. 1% RESISTORS RNC55J TYPE

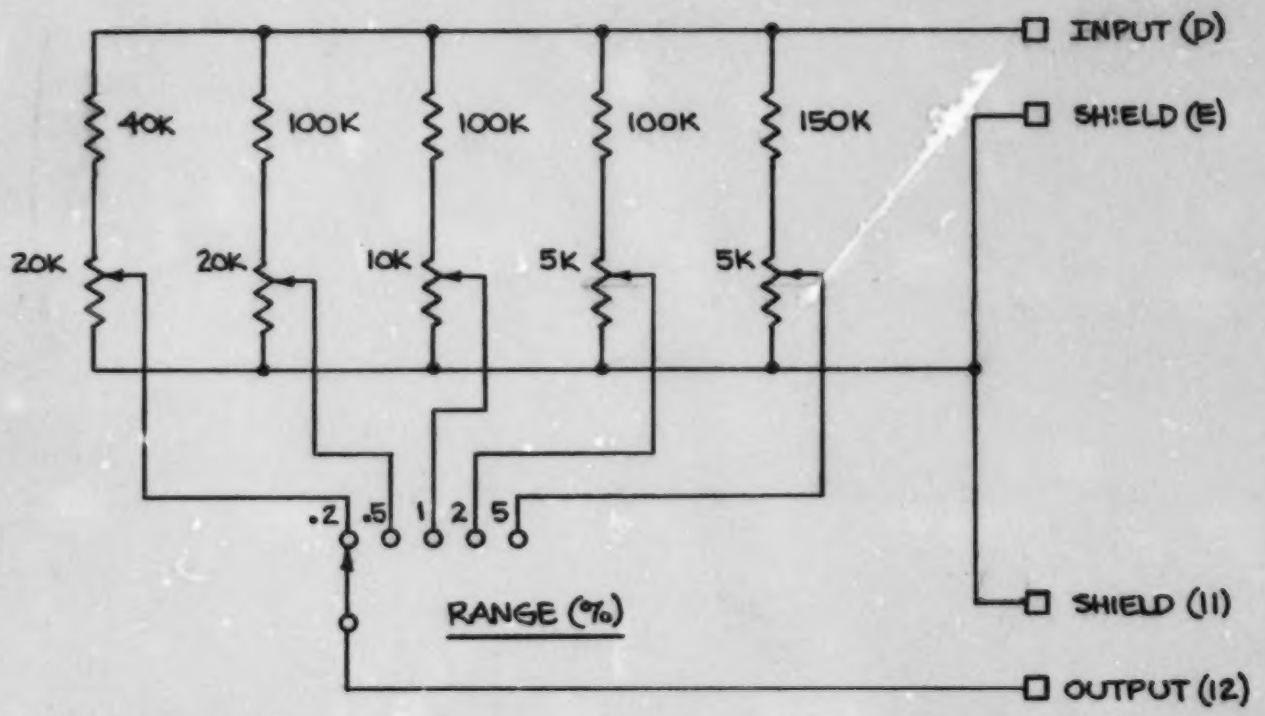

Figure 12. Wiring diagram of the range card. The ranges correspond to the numbers on the range switch, and represent the H_2O concentration that produces full-scale readings. A potentiometer is adjusted to change the sensitivity of a given range. The range card is located at the top of the instrument near the front, and is accessed by removing the top cover. The master span potentiometer on the main card is adjusted to change the sensitivities of all five ranges by the same factor.

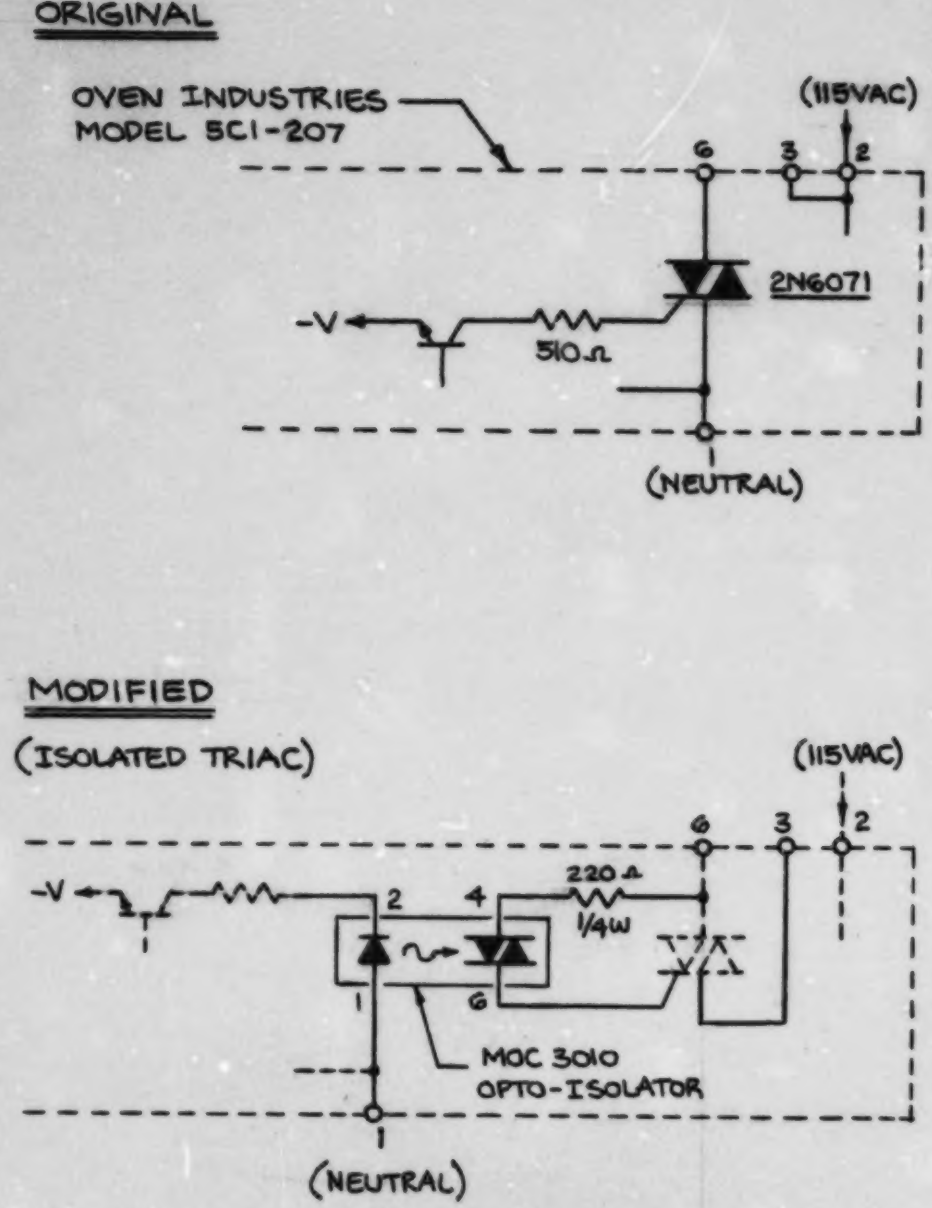

Figure 13. Electronic diagrams of the temperature controllers. The controller for the sample cell has been modified as indicated to isolate heater wires from the 115 VAC power line. The controller for the enclosure is in its original form.

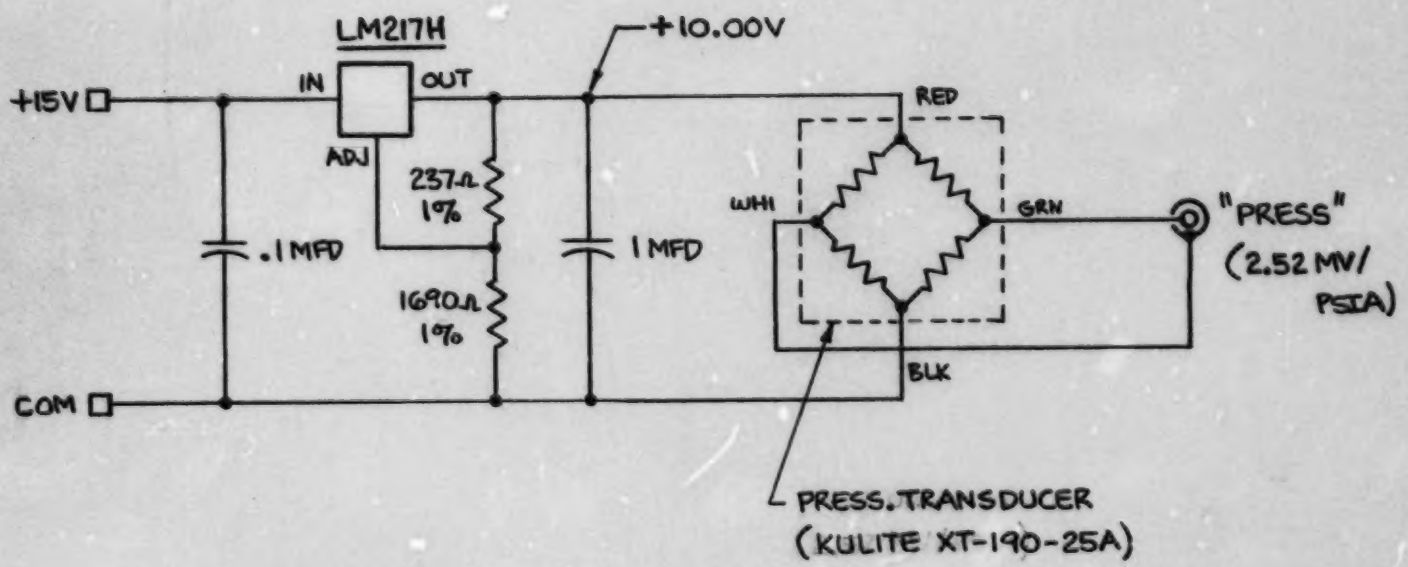

Figure 14. Wiring diagram for the pressure transducer. The pressure in the sample cell can be measured at the jack labeled "PRESS" on the front panel. The signal is 2.52 mV/psia, which is equivalent to 37.0 mV/atm absolute.

SECTION 9

REFERENCES

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5. Burch, D. E. and Pembrook, J. D., "Instrument to Monitor CH_4, CO and CO_2 in Auto Exhaust", Ford Aerospace and Communications Corp., Aeronutronic Division, Newport Beach, California.

6. Burch, D. E., Gryvnak, D. A. and Patty, R. R., "Absorption by H_2O between 2800 and 4500 cm^{-1}" Scientific Report Contract NONR 3560(00), Sept. 1965, ASTIA #AD626726.

7. Burch, D. E., Gryvnak, D. A. and Patty, R. R., "Absorption by CO_2 between 3100 and 4100 cm^{-1}" Scientific Report Contract NONR 3560(00), Apr. 1968, ASTIA #AD669468.

APPENDIX A

SUPPLEMENTAL INFORMATION ON KEY COMPONENTS

This appendix includes information not contained in the text on several of the key components obtained from outside vendors. Names of the suppliers or manufacturers are included:

Spectral Filters	λo = 2.59 μm (filter A) and 2.51 μm (filter B) 6.35 cm diam. x 1.5 mm thick. Infrared Industries, Waltham, MA.
Pbs Detector	2mm x 2mm; special type for long wave sensitivity at room temperature. (Infrared Industries)
Source	Tungsten-iodide bulb (G.E. Part No. 1974)
CaF_2 Lens #1	1/2" x 1/2" x 7/8"; one end flat; other end convex with 1/2" r. of c. (Gates Gem Co., Costa Mesa, CA)
CaF_2 Lens #2	1/2" x 1/2" x 2"; one end convex with 1/2" r. of c.; other end beveled at 45° and coated with aluminum. (Gates Gem Co., Costa Mesa, CA)
Spherical Mirror	20 cm r. of c. (Ealing)
Entrance Window	Sapphire rod, 5/16" diam.; one end convex with 1/2" r. of c. (Adolph Meller Co., Providence, R.I.)
Exit Window	Sapphire rod, 5/16" diam. by 0.70" long. Both ends are convex with 3/8" r. of c. (Adolph Meller Co., Providence, R.I.)
Motor	Synchronous, 1800 rpm. The voltage across to motor is dropped to about 85 VAC by a dropping resistor. (Bodine)
Pressure Transducer	Sensitivity, 37 mV/atm. Kulite Semiconductor Products, Inc., No. XT-190-25-PSIA
Temperature Controllers	Oven Industries, Inc. No. 5C1-207 with probe No. TP40
Thermocouples	Iron-Constantan. Sensitivity, 52 μV/°C.